

An Optical Satellite Tracking System for Undergraduate Research

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A commercial off-the-shelf satellite tracking system is developed and utilized for determining satellite characteristics on a minimum budget. A summary of the system components, developments, capabilities, and future improvements is addressed within this paper. The system is divided into four main components: camera and lens, tracking mount, tracking and data handling computer, and software. The system is highly mobile and has provided usable research data through the imaging of unresolved satellites as dim as 6th magnitude. Future plans for a permanent assembly with networked control and automated data collection is also described.

Nomenclature

Exposure - camera shutter time (seconds)

Magnitude - logarithmic measure of the brightness of an object

I. Introduction

Space situational awareness has become an increasingly important topic as we continue to populate space and rely on space assets. Traditionally large telescopes and expensive operation costs have been required to effectively track satellites. In the past couple of decades several systems have been developed to help reduce the associated costs [1, 2]. This project is an attempt to reduce the costs even more.

The following paper describes the system, the developments and improvements that have been made since the start of the project last year. First a summary of operations explains process of using the system, including pre-observations setup, recording data, and post processing the recorded data. The system components section provides a summary of all equipment utilized to run the system, and the details of each component within the system. A developments and capabilities section describes the limits of the system along with any problems that were encountered and the solutions to those problems. Finally a short explanation of the results of the system so far is listed to provide insight to the system's success.

II. Summary of Operation

The main components of the overall process include: pre-pass planning, equipment setup and calibration, data collection, and post observation data processing. The pre-pass planning phase consists of three elements. First, a weather prediction of sky coverage is used to make sure the observing time will have minimal cloud cover. The main source for this information is from the National Weather Service's Hourly Weather Forecast Graph for the local area, which can be found online. Second, pass predictions for the most visible satellites needs to be obtained. This information is generally obtained from Heavens-above.com, which provides information on visible passes from the observation site and magnitude predictions for the brightness of each satellite. From this information, satellite passes are chosen based on the quality of data that they will provide. Considerations include, the duration and orientation of the pass (a higher elevation pass visible from horizon to horizon is best), magnitude, pass time windows, previously recorded satellites, and dimensional data (if publicly available). The final pre-pass plan step is to obtain current two line element (TLE) orbit information for the satellites to be observed. The main source of TLE data is Space-Track.org. If this website does not contain the TLE data needed, the data is obtained from the Heavens-above.com. The setup phase consists of placing the tracking mount in position, applying power, mounting the camera and lens on the tracking mount, and connecting the camera and hand controller to the tracking computer via USB extension cables. The mount is then manually controlled to point at Polaris and the lens focus is adjusted as

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needed. The tracking mount is then aligned on Polaris. This calibrates the mount's sky pointing position, and is fairly accurate as long as the mount is on a level surface. Next a test satellite pass is used to test the alignment and adjust the lead/lag time of the tracking software driving the mount. Ideally the satellite should show up in the center of the frame, if not, the lead/lag time is adjusted to correct for time errors in the TLE or the computer clock. If this does not fix the problem, realignment is needed. Next, the planned satellite passes are recorded. Finally the resulting data is post processed into image sequences to contain positional pointing data used for analysis of the dimensional characteristics of each satellite.

III. System Components

A. System Equipment

The system includes all readily available commercial equipment found in Table 1 below. All equipment pricing is quoted from currently available online sources. This table shows that anyone with a need for optical tracking can replicate this system with only a relatively small initial investment.

Table 1: System Equipment Listing with Prices		
Part	Product/Description	Price
Camera	The Imaging Source DMK 41AU02.AS (Monochrome, 1280x960)	\$630
Lens	Nikon 35mm f/1.8G AF-S DX	\$200
Tracking Mount	Celestron Nexstar 6SE Mount	\$700 (w/ telescope)
USB Cables	2 X 20m USB 2.0 cable	\$30 (each)
Mount AC Power Adaptor	Celestron AC Adaptor	\$20
Computer-to-Mount drive cable	Celestron Nexstar RS232 PC Interface Cable	\$16
Serial-to-USB Converter	Generic USB-to-Serial Adaptor w/cable	\$20 (avg)
Power Extension Cable	Generic Extension AC Power Cable	\$25 (avg)
Laptop	Toshiba Qosmio 17inch Notebook	\$1400
Camera Hard Case	Generic Medium Hard Case (non-waterproof)	\$35 (avg)
Lens UV Protective Filter	Nikon 52mm Filter	\$24
Dovetail Mount	ADM Accessories Vixen Series to D Series Adapter	\$109
C-Mount	C-mount adaptor for Nikon Camera Lens	\$79
GPS	GPS-18 USB	\$67
Total		\$3385

B. Camera and Lens

The camera used for this system is manufactured by The Imaging Source. The following are the cameras specifications provided by the manufacturers. The camera's sensor is a ½ inch Sony ICX205AL progressive scanning CCD chip with a resolution of 1280 by 960 pixels, the exposure limits are from 1/10000th of a second to 60 minutes, and selectable frame rates of 15, 7.5, and 3.75 frames per second, it uses a USB 2.0 interface for power and connection to the computer, and is a cube of 5.0 cm on each side. This camera is sold for astronomy uses. The lens utilized for this system is a Nikon 35mm f/1.8G. It provides an approximately 12 degree field of view when coupled with the above camera. Finally, a C-mount adaptor must be used to convert the lens connection to the threaded camera connection.



Figure 1: Camera and Lens

C. Tracking Mount

A commercially available azimuth/elevation telescope mount with accompanying handheld controller from Celestron is utilized in this system. The hand controller provides either manual control of the mount or computer control via a serial computer connection and software. The hand controller can be used to align the mount and point at celestial objects but will not allow the mount to track satellites as a standalone device. To track satellites the hand controller must be connected to a computer to drive the mount via tracking software that sends real time azimuth and elevation command inputs during a satellite pass.



Figure 2: Camera/Lens on Tracking Mount

D. Tracking and Data Handling Computer

The current setup utilizes a desktop replacement classed Toshiba brand laptop. This computer is utilized to drive the tracking mount and record video data during operation. After data recording, the computer is utilized to post process the recorded data into usable data for determining satellite characteristics. The same computer is also used for pre-pass planning. For the current system setup a laptop allows the setup to be highly mobile. In the future the setup could be adapted to be more permanent and the computer will be remotely controlled off station via an internet or local network connection. On the mobility side, preliminary tests have been run using a netbook (~\$250). Indications are that a small inexpensive netbook would be able to run the associated software with no compromises except for screen resolution if substituted for the tracking and data handling computer. The biggest computational draw is post-processing, which may still have to be done on a larger computer.



Figure 3: Tracking & Data Handling Computer

E. Associated Software

Initially the system setup utilized the following software: Satellite Tracker, IC Capture (astronomy version 2.2), and Matlab. Additionally, Google Earth, VirtualDub, Iris, and SkyTools3 were utilized as secondary software for reference and post processing. Google Earth was used to determine an accurate latitude, longitude, and altitude position for the observing site. Skytools3 was utilized for alignment, accuracy checks, and system characterization. Satellite Tracker is the software used to drive the mount to track the satellites using the TLEs provided to it in a text file. This software also predicts passes, but it does not provide a magnitude estimate for the predictions. IC Capture is software provided by The Imaging Source with the camera. It allows for full control of the camera and video recording in .avi format. Matlab was initially utilized only for data processing. VirtualDub is a freeware program utilized as a tool to break up the video recordings into image sequences. Iris is also a freeware program and used to normalize each frame to the satellite's position. The software then analyzes the satellite's brightness value in each frame recorded, providing an output data file of the brightness information. This initial setup consisted entirely of commercial off-the-shelf hardware and software. It can be implemented by anyone for a relatively small cost. Improvements, some of which taken away from the commercial off-the-shelf nature of the system, are described in section IV.

F. Pass Predictions & TLE Sources

During pre-observation planning, visible satellite passes are estimated using Heavens-above.com. This site is utilized over pass prediction software because it is easy to use and free of charge, and also because Heavens-above provides an estimated magnitude value for each pass. The magnitude value is needed so that the exposure can be estimated for the camera to insure consistent recordings. This also guarantees an estimate that the satellite can be observed within the limits of the setup. Additionally, the website provides these predictions in a listed format, so a plan can be developed to maximize the number of passes that can be observed. This is accomplished by using the rise and set times, and allowing for about a two minute window of transition to reposition the camera to the next satellite's rise position. The best way to create an observation schedule is to copy the Heavens-above table into Microsoft Excel. This allows for the highlighting of the passes to be observed, exposure estimates to be calculated, and notes to be taken during the pass that can be easily saved.

To accurately track the satellites, a TLE source with the most up to date TLEs is needed. The satellite TLEs were acquired from Space-track.org. This website requires a user to register with the site for access, but provides TLEs updated daily from NORAD in a text file format. They can also be copied directly from the site to a blank text file. An alternative website that does not require a login for the most current TLEs is celestrak.com. This website provides lists of the TLEs by the satellites mission type, and the listings must be copied from the webpage to a text file. TLEs for some objects that are not available on Space-track.org³ or celestrak.com [4] can be found on Heavens-above.com [5]. These TLEs are from an unknown source, but have been found to accurately predict satellite location. The solution to the lack of TLEs from Space Track is to copy the TLEs from the orbit page for the satellite on Heavens-above and paste them into the TLE file utilized for the observations. After observations are made, the TLE data text files are saved for future reference and post processing of data.

IV. Developments and Capabilities

This section will describe the system components and their discovered capability limits. Problems with each component will be addressed with some solutions or recommended alternatives provided. Developments and improvements to the system that have been implemented will be described in detail.

Several operational limits of the camera were explored. The camera takes time to start and stop acquiring frames; the device lags typically less than half of one second every time it is commanded to stop or start acquiring data. While acquiring data the camera has shown some signs of dropping frames and has moments of lagging/hang ups during recording; this is noted from the video play back. The loss of one frame from a pass of 600 or more frames is not detrimental to data reduction involving light intensity analysis. However this problem has caused accuracy concerns if this data is used in the future to determine orbital elements. This is one reason the current research has focused on characterization of the satellite itself by observing changes in brightness.

Figure 5 is an example of a raw data from from a satellite tracking session where the satellite is the dot near the center of the image and the streaks are from nearby stars.



Figure 5: Example of Raw Data Frame.

For research involving satellite brightness data, a relation between exposure and object magnitude and a test of the system's recording limit was needed to define how dim an object it can record were both needed. The magnitude to exposure relation was developed from test runs of differing gain and exposure values to maximize the background stars and minimize their streaks with the satellite in frame. From observing the playbacks, the highest quality video was chosen as the desired result of future data. The video settings of gain and exposure were the only setting changed. The gain value was set to stay the same and the exposure value became the variable to relate to magnitude. Using the astronomy equation for magnitude an equation relating magnitude to exposure time was determined to be the following:

$$Exposure = \frac{0.3}{2.512^{(2.5 - \text{magnitude})}} \quad (1)$$

This equation is specific for this setup and was developed by Lt Col Thomas. This equation is tied to systems with the same camera and lens configuration. Also this equation normalizes the images to have the same background to satellite brightness relation. For the dimmest object system recording limit, the test consisted of using the histogram plot observing a known magnitude stationary object, the 4.3 magnitude Andromeda galaxy, and observing when the image background was too saturated to be used for analysis. The test was performed with IC Capture in live view mode window with the settings of 950 for gain and brightness of zero. The exposure value was increased until the histogram showed a majority of the pixels having values in the upper half of the range and the image showed signs of background saturation. The test yielded a maximum exposure of 9.709 seconds which means the maximum satellite magnitude observation limit of 6.2749 based off equation one. Testing was done on two satellites, Cosmos 2233 and Spot 1/Viking Rocket, the first with magnitude 5.6 and the other with magnitude 5.2. They proved that with 4.741 and 3.4 second exposures that a satellite could stay in the center frame for a long exposure and not streak by utilizing estimates of equation 1. So dim objects can be tracked without any issues, but provide less data due to a smaller sampling rate.

Additionally an error in how far off the time stamp is relative to each observing image was accessed for characterization of the system's current setup. This error was observed to vary with exposure, but it is typically less than 0.09 to 0.06 seconds off. This estimate is based on a test using internally developed Matlab software. The test consisted of calculating the time from when the camera is triggered to when it checks if the exposure is completed. The exposure time is subtracted off this total time. It was assumed that the check to determine if the exposure was completed was infinitely small with this assumption, the difference in total time and the exposure time yielded the time error. Also, the accessing of the system clock for the time step takes less than a millisecond. A test like this could not be completed on IC Capture due to the inability to access the source code to setup the needed test lines for

timing the processes. Tests were run though that show that the starting time stamp values written to the recording files are accurate to the nearest second.

The computer used in the setup is powerful enough to record and process the videos with no issues other than the power settings that can limit the processors speed. Newer computing processors used in this newer computer have power saving settings which step down the processing speed with usage to conserve energy. The power settings within Windows need to be set to 'High Performance' mode. Also the computer needs to be run on the AC power adaptor and not the battery to reduce lagging in the programs utilized for tracking.

Limits on the tracking mount have surfaced resulting in some slew/positional limits for accurately recording a satellite. The main limitation of the mount is that observation passes that have maximum elevation values above 80 degrees will create high slew rates that could reach the maximum slew limit of the azimuth axis of the mount. Additionally, the higher elevation passes and slew rates will cause the recording to lose sight of the satellite for the amount of time it takes the mount slew its azimuth axis around to track the descent of the satellite's pass. The reason the mount swivels around instead of tracking over the top is due to the fact it is designed for telescopes. This creates an elevation limit of 90 degrees and requires the mount to track the ascending path of the satellite to nearly max elevation before it must swivel around to track the descent of the pass. A possible solution to this problem might be to adjust the maximum elevation limit in Satellite Tracker or within the Nexstar handheld controller. The high slew rate passes tend to cause slight misalignment for future passes. This could be an issue created by the encoders the mount utilizes to measure its current pointing position as it slews. The former issue is only a hypothesis; there has been an observed minor difference in a satellite's initial position in frame following a high rate pass. The issue has not been prominent enough to cause large errors, but should be noted for future development at higher magnifications.

Furthermore, the mount has sensitive setup limits for alignment and the precision of the alignment is limited due to the low magnification of the lens currently used. The mount must be leveled before each observation run, because the mount is moved after each session. The leveling insures the accuracy of the alignment of the mount with the sky. This must be done because the scope might not align, but even if it does align, it might not align accurately enough to frame the satellite correctly as it is tracked. The precision of the alignment due to the lens used is not a prominent issue but must be taken into account when aligning the mount because one needs to be as consistent as possible when centering objects in the frame when accomplishing the alignment process. If this minor issue is not kept in mind, issues could occur trying to keep the satellite framed in the center throughout a pass due to the slight drift of the satellite in the frame over the course of a pass (a nominal occurrence.) The issue of the mount failing to align at all causes valuable time to be lost during the setup process.

Additionally, it must be noted that most of the alignments for observation runs have utilized the solar system object alignment method by aligning on Jupiter. The team initially used the three star alignment methods and had some difficulties with alignment due to the needed precision centering an object in frame. This caused large delay in setup time and the missing of planned observations. Because Jupiter was visible sufficiently before the brighter stars were and during this part of the project's time, the team utilized the solar system object alignment method. It proved to be the quickest and sometimes most accurate alignment due to the fact one uses a planet as the only object that has to be centered in the frame.

Originally, several different freeware programs were used to provide the full range of functionality necessary for this project. The telescope mount's hand controller was used to align the scope, usually with three individual stars or planets. The program Satellite Tracker was used to connect to the telescope and track satellites based on pre-prepared TLEs. IC Capture 2.2 was used to connect to the camera and record video of the pass. For initial data reduction VirtualDub was used to separate the video out into individual frames for analysis. Ideally, software could be developed that combines all of these abilities into only one program. While this has not yet been accomplished, significant steps have been taken towards this goal.

Currently, two Matlab GUIs have been created that combine the functionality of the hand controller, Satellite Tracker, IC Capture, and VirtualDub. The first, FSTrack, was developed to provide mount control and tracking. FSTrack has the ability to align the scope, if it is situated on a level surface, and update that alignment if the setup is moved. It can update the computer's system clock if necessary from the USNO website including a user input UTC offset. Different observation locations can be preprogrammed into a separate file that will read in the specified location for use in providing tracking information. FSTrack can also get cloud coverage data from

weatherunderground.com for the specified ground location. FSTrack will also load pass prediction data for satellites as low as 4.5 magnitude from Heavens-above.com. This information includes satellite NORAD number, pass duration, times, max elevation, and azimuth and elevation data for pass beginning and ending. This information is also specific to the ground location. In terms of mount control, FSTrack includes four way direction controls that can be used to calibrate the mount by pointing it at Polaris. It will also allow the telescope to track satellites from TLEs loaded into a text file. A lag, lead feature allow the program to delay or speed up tracking in order to center the satellite in the frame. This is often necessary if the TLE's are old or the computer clock was not updated recently. All of this functionality was originally included in Satellite Tracker, the mount's hand controller, and manually accessing Heavens-above.com and weather sites. A second Matlab program, FSCamera, was developed to incorporate the functionality of IC Capture and VirtualDub. FSCamera is able to interface with the camera to provide a live preview of the image and record data. The images are recorded as an image sequence as opposed to a video file, eliminating the need for VirtualDub altogether. FSCamera saves each image with the name of the satellite, the frame number, the time stamp from that exposure, and the mount's azimuth and elevation at the time of the exposure. IC Capture was not able to communicate with Satellite Tracker; so azimuth and elevation data was never available. Currently, this information is derived from the input TLEs. However, in the future, this collected data could contribute to orbit determination projects for satellites with unknown TLEs. While IC Capture has more control over some aspects of the camera including white balance, brightness, contrast, etc. FSCamera only included the ability to control exposure and gain, as it was found that these were the only controls necessary to achieve proper picture quality.

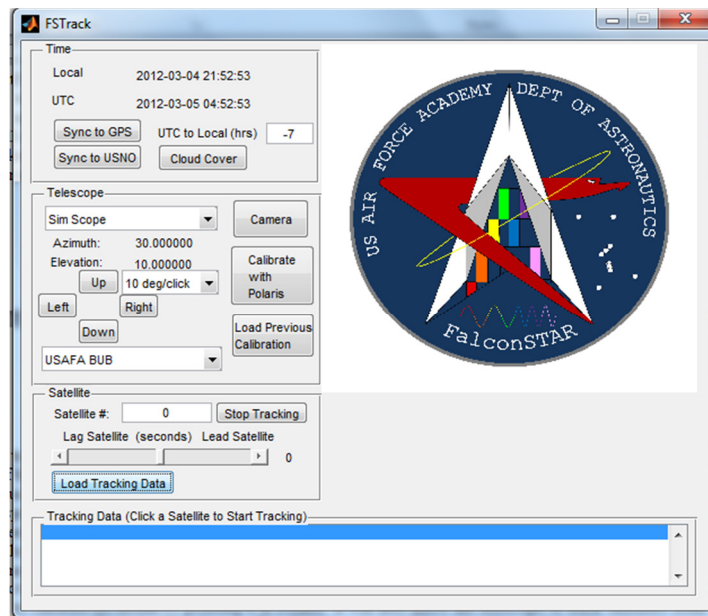


Figure 4: Screen shot of FSTrack

The system as a whole is designed as a mobile setup which creates positive and negative limitations. Without a permanent shelter for the mount setup, one has to take the mount out to the observation location each session, level it, reset the handheld clock, focus the camera, and align the mount. This causes longer setup times resulting from the tedious setup process. If in the future a permanent location could be acquired, the mount would not have to be repositioned and aligned for each test, because the mount can be “parked” in its last known configuration. If this solution becomes available the setup time would be limited only by starting up the computer tracking software and doing a quick alignment check.

V. Results

Once the limitations of the setup were understood, the idea of determining satellite size or aspect ratio based off brightness was set as the research goal. This goal has shown some promising results as development in the model used to draw this information out of the observation data is being collected. This goal not only requires data recordings, but ways to determine the true brightness of the satellite. The true brightness is determined by taking into account the effects of the atmosphere and illumination due to the observing angle and the angle of the sun to the

satellite. By taking into account these factors and comparing the results with the ideal case of a perfect spherical satellite, a model for the size ratio of the observed satellite has been developed.

VI. Conclusion

Over the course of past six months this low cost, portable satellite tracking system has been developed, tested, and improved upon a number of times. Future improvements of a permanent remotely controllable system are being developed to further the system's usefulness. Additionally, automation software is being developed to help make the system more efficient to use and gather data so more time can be focused on the determination of the characteristics of the satellite. The system has provided data to develop a mathematical reduction model to determine satellite dimensional characteristics based solely of their recorded light intensity curves.

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